

NITRIDE-BASED TRANSISTORS WITH A PROTECTIVE LAYER AND A LOW-DAMAGE RECESS AND METHODS OF FABRICATION THEREOF

STATEMENT OF GOVERNMENT INTEREST

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5 FIELD OF THE INVENTION

The present invention relates to semiconductor devices and, more particularly, to transistors that incorporate nitride-based active layers.

BACKGROUND

10 Materials such as silicon (Si) and gallium arsenide (GaAs) have found wide application in semiconductor devices for lower power and (in the case of Si) lower frequency applications. These, more familiar, semiconductor materials may not be well suited for higher power and/or high frequency applications, however, because of their relatively small bandgaps (*e.g.*, 1.12 eV for Si and 1.42 for GaAs at room  
15 temperature) and/or relatively small breakdown voltages.

In light of the difficulties presented by Si and GaAs, interest in high power, high temperature and/or high frequency applications and devices has turned to wide bandgap semiconductor materials such as silicon carbide (2.996 eV for alpha SiC at room temperature) and the Group III nitrides (*e.g.*, 3.36 eV for GaN at room  
20 temperature). These materials, typically, have higher electric field breakdown strengths and higher electron saturation velocities as compared to gallium arsenide and silicon.

A device of particular interest for high power and/or high frequency applications is the High Electron Mobility Transistor (HEMT), which is also known  
25 as a modulation doped field effect transistor (MODFET). These devices may offer operational advantages under a number of circumstances because a two-dimensional electron gas (2DEG) is formed at the heterojunction of two semiconductor materials with different bandgap energies, and where the smaller bandgap material has a higher

electron affinity. The 2DEG is an accumulation layer in the undoped ("unintentionally doped"), smaller bandgap material and can contain a very high sheet electron concentration in excess of, for example,  $10^{13}$  carriers/cm<sup>2</sup>. Additionally, electrons that originate in the wider-bandgap semiconductor transfer to the 2DEG, allowing a high electron mobility due to reduced ionized impurity scattering.

This combination of high carrier concentration and high carrier mobility can give the HEMT a very large transconductance and may provide a strong performance advantage over metal-semiconductor field effect transistors (MESFETs) for high-frequency applications.

High electron mobility transistors fabricated in the gallium nitride/aluminum gallium nitride (GaN/AlGaN) material system have the potential to generate large amounts of RF power because of the combination of material characteristics that includes the aforementioned high breakdown fields, their wide bandgaps, large conduction band offset, and/or high saturated electron drift velocity. A major portion of the electrons in the 2DEG is attributed to polarization in the AlGaN.

HEMTs in the GaN/AlGaN system have already been demonstrated. U.S. Patents 5,192,987 and 5,296,395 describe AlGaN/GaN HEMT structures and methods of manufacture. U.S. Patent No. 6,316,793, to Sheppard et al., which is commonly assigned and is incorporated herein by reference, describes a HEMT device having a semi-insulating silicon carbide substrate, an aluminum nitride buffer layer on the substrate, an insulating gallium nitride layer on the buffer layer, an aluminum gallium nitride barrier layer on the gallium nitride layer, and a passivation layer on the aluminum gallium nitride active structure.

One step in the fabrication of nitride-based transistors is the formation of ohmic contacts for such transistors. The formation of ohmic contacts has, typically, required high annealing temperatures (e.g. 900 °C). Such high annealing temperatures may damage the materials and/or the device.

For example, in conventional devices utilizing high annealing temperatures when forming ohmic contacts, the sheet resistance of a gate region (defined as the active device region between the two contacts) of AlGaN and/or GaN layers typically increases in comparison to sheet resistances of the AlGaN and/or GaN layers as-grown. Such an increase in sheet resistance is believed to detrimentally affect the device.

## SUMMARY OF THE INVENTION

Embodiments of the present invention provide for fabricating a transistor by forming a nitride-based semiconductor barrier layer on a nitride-based semiconductor channel layer and forming a protective layer on a gate region of the nitride-based semiconductor barrier layer. Patterned ohmic contact metal regions are formed on the barrier layer and annealed to provide first and second ohmic contacts. The annealing is carried out with the protective layer on the gate region. A gate contact is also formed on the gate region (*e.g.*, the active device region between the first and second ohmic contacts) of the barrier layer.

In further embodiments of the present invention, the protective layer is removed subsequent to annealing the patterned ohmic contact metal. The protective layer may be an aluminum nitride layer. The protective layer may be removed utilizing a low damage etching technique. For example, the low damage etching technique may include wet removal with a strong base, such as KOH. After removing the protective layer a passivation layer may be formed on exposed portions of the barrier layer. In these embodiments, the gate contact may be formed by etching a recess in the passivation layer utilizing a low damage etch technique to expose a portion of the gate region of the barrier layer and forming the gate contact in the recess in the passivation layer.

In additional embodiments of the present invention, the passivation layer is formed on exposed portions of the barrier layer and the protective layer. In these embodiments, the gate contact may be provided by forming a gate contact that  
5 extends through the passivation layer and the protective layer to contact the barrier layer.

In yet other embodiments of the present invention, forming a protective layer includes forming a patterned protective layer on the barrier layer. The patterned protective layer covers a first portion of the barrier layer corresponding to the gate  
10 region and exposes adjacent second portions of the barrier layer corresponding to the first and second ohmic contacts. The patterned ohmic contact metal regions are provided by forming patterned ohmic contact metal regions on the second portions of the barrier layer. The patterned ohmic contact metal regions are adjacent and spaced apart from the patterned protective layer.

15 In still further embodiments of the present invention, forming the patterned protective layer includes blanket depositing a protective layer material on the barrier

layer, forming a mask, typically photoresist, on the blanket deposited protective layer material, the mask having windows corresponding to locations of the first and second ohmic contacts, etching the blanket-deposited protective layer through the windows utilizing a low damage etching technique and removing the mask. The windows  
5 corresponding to locations of the first and second ohmic contacts may be larger than an area of the first and second ohmic contacts. The low damage etching technique may be one or more of RIE, ECR, downstream plasma and/or ICP using  $\text{CF}_4/\text{O}_2$ ,  $\text{NF}_3/\text{O}_2$  and/or other fluorinated species.

Forming the gate contact may include etching a recess in the patterned  
10 protective layer that exposes a portion of the first portion of the barrier layer and depositing a gate contact in the recess. Forming a recess may include forming a mask on the patterned protective layer, the mask having a window corresponding to location of the recess, etching the patterned protective layer through the window utilizing a low damage etching technique and removing the mask. The low damage  
15 etching technique utilized to etch the patterned protective layer may include RIE, ECR, downstream plasma and/or ICP using  $\text{CF}_4/\text{O}_2$ ,  $\text{NF}_3/\text{O}_2$  and/or other fluorinated species.

In particular embodiments of the present invention, the protective layer includes  $\text{SiN}$ ,  $\text{AlN}$  and/or  $\text{SiO}_2$ . The  $\text{SiN}$ ,  $\text{AlN}$  and/or  $\text{SiO}_2$  may be non-stoichiometric  
20 and can have compressive or tensile strain. The protective layer may be deposited using physical vapor deposition (PVD) and/or chemical vapor deposition (CVD).

In yet additional embodiments of the present invention, a passivation layer is formed on the patterned protective layer so as to substantially fill gaps between the patterned protective layer and the first and second ohmic contacts. The patterned  
25 protective layer and the passivation layer may be the same or different materials. For example, the patterned protective layer may be aluminum nitride and the passivation layer may be silicon nitride. Alternatively, the patterned protective layer and the passivation layer may be silicon nitride.

In still other embodiments of the present invention, the patterned protective  
30 layer is removed so as to expose the first portion of the barrier layer. Removing the patterned protective layer may be followed by forming a passivation layer on exposed portions of the barrier layer. In such embodiments, the patterned protective layer may be aluminum nitride and the passivation layer may be silicon nitride.

In further embodiments of the present invention, formation of the gate contact is preceded by forming the passivation layer. The gate contact is provided by forming a recess in the passivation layer that exposes a portion of the first portion of the barrier layer and forming a gate contact in the recess. Forming the recess may include  
5 forming a mask on the passivation layer. The mask has a window corresponding to location of the recess. The passivation layer is etched through the window utilizing a low damage etching technique and the mask is then removed.

In particular embodiments of the present invention, the nitride-based channel layer and the nitride-based semiconductor barrier layer are Group III-nitride layers.  
10 For example, the channel layer may have a composition of  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  wherein  $0 \leq x < 1$ , where the bandgap of the channel layer is less than the bandgap of the barrier layer. The channel layer could also be aluminum gallium nitride (AlGaN), gallium nitride (GaN), indium gallium nitride (InGaN), and/or aluminum indium gallium nitride (AlInGaN) and the barrier layer could be aluminum nitride (AlN), aluminum indium  
15 nitride (AlInN), AlGaN, GaN, InGaN, and/or AlInGaN. The barrier layer and/or the channel layer may be multiple layers. A buffer layer may also be formed on a substrate and the channel layer formed on the buffer layer to provide the nitride-based channel layer. The channel layer and the barrier layer may be configured to provide a High Electron Mobility Transistor (HEMT). The nitride-based channel layer may be  
20 provided on a SiC substrate.

In still further embodiments of the present invention, the formation of the gate contact is preceded by the formation of a passivation layer. The formation of the gate contact the includes forming a recess in the passivation layer and the patterned protective layer that exposes a portion of the first portion of the barrier layer and  
25 forming a gate contact in the recess.

In particular embodiments of the present invention, the protective layer is formed to a thickness of at least about a thickness of the ohmic contact material. The protective layer may also have a thickness of at least about two monolayers. In particular, the protective layer may have a thickness of from about 1 nm to about 500  
30 nm.

In yet other embodiments of the present invention, a high electron mobility transistor includes a nitride-based channel layer on a substrate and a nitride-based semiconductor barrier layer on the nitride-based channel layer. The channel of

electrons at the interface between the channel and barrier layers has a sheet resistance that is substantially the same as an as-grown sheet resistance of the nitride-based HEMT channel. Ohmic contacts and a gate contact are provided on the barrier layer.

5 The high electron mobility transistor may further include a protective layer disposed on the barrier layer that is adjacent and spaced apart from the ohmic contacts and that the gate contact extends through. A passivation layer may also be provided on the protective layer and that substantially fills a gap between the ohmic contacts and the protective layer. The passivation layer may also be on the protective layer and the gate contact may extend through the protective layer and the passivation layer.  
10 The gate contact may be also be provided directly on the protective layer. The passivation layer on the barrier layer may substantially fill a gap between the ohmic contacts and the gate contact.

In particular embodiments of the present invention, the nitride-based channel layer and the nitride-based semiconductor barrier layer each include a Group III-  
15 nitride layer. The channel layer may have a lower bandgap than the barrier layer. The channel layer may include an undoped layer having a thickness of greater than about 20 Å. The channel layer may also include a superlattice and/or a combination of Group III-nitride layers. The channel layer may include aluminum gallium nitride (AlGa<sub>N</sub>), gallium nitride (Ga<sub>N</sub>), indium gallium nitride (InGa<sub>N</sub>), and/or aluminum  
20 indium gallium nitride (AlInGa<sub>N</sub>). The barrier layer may include aluminum nitride (Al<sub>N</sub>), aluminum indium nitride (AlIn<sub>N</sub>), AlGa<sub>N</sub>, Ga<sub>N</sub>, InGa<sub>N</sub>, and/or AlInGa<sub>N</sub>. For example, the barrier layer may include Al<sub>x</sub>Ga<sub>1-x</sub>N wherein 0 < x < 1. The barrier layer may include multiple layers. A buffer layer may also be provided on the substrate, where the nitride-based channel layer is disposed on the buffer layer.

25 In still further embodiments of the present invention, the protective layer has a thickness of at least about a thickness of the ohmic contacts. The ohmic contacts may also have a contact resistance of less than about 1 Ω-mm.

In yet other embodiments of the present invention, a high electron mobility transistor includes a nitride-based channel layer on a substrate, a nitride-based  
30 semiconductor barrier layer on the nitride-based channel layer, a protective layer on the barrier layer, ohmic contacts on the barrier layer, adjacent and spaced apart from the protective layer so as to provide a gap between the ohmic contacts and the protective layer and a gate contact on the barrier layer and extending through the

protective layer. A passivation layer may also be provided on the protective layer and that substantially fills the gap between the ohmic contacts and the protective layer.

In still further embodiments of the present invention, fabrication of a transistor includes forming a nitride-based semiconductor barrier layer on a nitride-based semiconductor channel layer and forming a protective layer on a gate region of the nitride-based semiconductor barrier layer. Patterned ohmic contact metal regions are formed on the barrier layer. The patterned ohmic contact metal is annealed to provide first and second ohmic contacts, for example, source and drain contacts. A recess is etched in the protective layer in a gate region of the barrier layer utilizing a low damage etch technique to expose a portion of the gate region of the barrier layer. The gate contact is formed in the recess in the passivation layer.

In particular embodiments of the present invention, the protective layer comprises a passivation layer. The protective layer may, for example, be an  
5 aluminum nitride layer, a silicon nitride layer and/or a silicon dioxide layer or layers. The low damage etching technique may be a wet etch using a strong base. In certain embodiments of the present invention, annealing the patterned ohmic contact metal to provide first and second ohmic contacts is carried out prior to forming a protective layer. In other embodiments of the present invention, annealing the patterned ohmic  
10 contact metal to provide first and second ohmic contacts is carried out subsequent to forming a protective layer.

#### BRIEF DESCRIPTION OF THE DRAWINGS

**Figures 1A-1F** are schematic drawings illustrating fabrication of a transistor  
15 according to embodiments of the present invention.

**Figures 2A and 2B** are schematic drawings illustrating operations in the fabrication of a transistor according to further embodiments of the present invention.

**Figure 3** is a schematic illustration of an alternative fabrication step according to embodiments of the present invention.

**Figure 4** is a schematic illustration of a transistor according to further  
20 embodiments of the present invention.

**Figure 5** is a schematic illustration of a transistor according to further embodiments of the present invention.

## DETAILED DESCRIPTION OF EMBODIMENTS OF THE INVENTION

The present invention now will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these  
5      embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout. Furthermore, the various layers and regions illustrated in the figures are illustrated schematically. Accordingly, the present  
10     invention is not limited to the relative size, spacing and alignment illustrated in the accompanying figures. As will also be appreciated by those of skill in the art, references herein to a layer formed "on" a substrate or other layer may refer to the layer formed directly on the substrate or other layer or on an intervening layer or layers formed on the substrate or other layer. It will also be appreciated by those of  
15     skill in the art that references to a structure or feature that is disposed "adjacent" another feature may have portions that overlap or underlie the adjacent feature.

Embodiments of the present invention utilize a protective layer and/or a low damage recess fabrication technique to reduce gate leakage and/or provide a high quality Schottky contact in a semiconductor device, such as a transistor. The use of a  
20     protective layer may reduce damage to the semiconductor in the gate region of the transistor that may occur during an anneal of ohmic contacts of the device. Thus, high quality gate and ohmic contacts may be provided with reduced degradation of the gate region that may result from formation of the ohmic contacts.

Embodiments of the present invention may be particularly well suited for use  
25     in nitride-based HEMTs such as Group III-nitride based devices. As used herein, the term "Group III nitride" refers to those semiconducting compounds formed between nitrogen and the elements in Group III of the periodic table, usually aluminum (Al), gallium (Ga), and/or indium (In). The term also refers to ternary and quaternary compounds such as AlGaN and AlInGaN. As is well understood by those in this art,  
30     the Group III elements can combine with nitrogen to form binary (*e.g.*, GaN), ternary (*e.g.*, AlGaN, AlInN), and quaternary (*e.g.*, AlInGaN) compounds. These compounds all have empirical formulas in which one mole of nitrogen is combined with a total of



one mole of the Group III elements. Accordingly, formulas such as  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  where  $0 \leq x \leq 1$  are often used to describe them.

Suitable structures for GaN-based HEMTs that may utilize embodiments of the present invention are described, for example, in commonly assigned U.S. Patent 6,316,793 and U.S. Patent Publication No. 2002/0066908A1 filed July 12, 2001 and published June 6, 2002, for "ALUMINUM GALLIUM NITRIDE/GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTORS HAVING A GATE CONTACT ON A GALLIUM NITRIDE BASED CAP SEGMENT AND METHODS OF FABRICATING SAME," U.S. provisional application serial no. 60/290,195 filed May 11, 2001 for "GROUP III NITRIDE BASED HIGH ELECTRON MOBILITY TRANSISTOR (HEMT) WITH BARRIER/SPACER LAYER," United States Patent Publication No. 2002/0167023A1 to Smorchkova *et al.*, published November 14, 2002, entitled "GROUP-III NITRIDE BASED HIGH ELECTRON MOBILITY TRANSISTOR (HEMT) WITH BARRIER/SPACER LAYER" and United States Patent Application Serial No. 10/617,843 filed July 11, 2003 for "NITRIDE-BASED TRANSISTORS AND METHODS OF FABRICATION THEREOF USING NON-ETCHED CONTACT RECESSES," the disclosures of which are hereby incorporated herein by reference in their entirety.

Fabrication of embodiments of the present invention is schematically illustrated in **Figures 1A-1E**. As seen in **Figure 1A**, a substrate **10** is provided on which nitride based devices may be formed. In particular embodiments of the present invention, the substrate **10** may be a semi-insulating silicon carbide (SiC) substrate that may be, for example, 4H polytype of silicon carbide. Other silicon carbide candidate polytypes include the 3C, 6H, and 15R polytypes. The term "semi-insulating" is used descriptively rather than in an absolute sense. In particular embodiments of the present invention, the silicon carbide bulk crystal has a resistivity equal to or higher than about  $1 \times 10^5 \Omega\text{-cm}$  at room temperature.

Optional buffer, nucleation and/or transition layers (not shown) may be provided on the substrate **10**. For example, an AlN buffer layer may be provided to provide an appropriate crystal structure transition between the silicon carbide substrate and the remainder of the device. Additionally, strain balancing transition layer(s) may also be provided as described, for example, in commonly assigned United States Patent Publication 2003/0102482A1, filed July 19, 2002 and published

June 5, 2003, and entitled "STRAIN BALANCED NITRIDE HETEROJUNCTION TRANSISTORS AND METHODS OF FABRICATING STRAIN BALANCED NITRIDE HETEROJUNCTION TRANSISTORS, and United States Provisional Patent Application Serial No. 60/337,687, filed December 3, 2001 and entitled

5 "STRAIN BALANCED NITRIDE HETEROJUNCTION TRANSISTOR," the disclosures of which are incorporated herein by reference as if set forth fully herein.

Silicon carbide has a much closer crystal lattice match to Group III nitrides than does sapphire ( $\text{Al}_2\text{O}_3$ ), which is a very common substrate material for Group III nitride devices. The closer lattice match may result in Group III nitride films of  
10 higher quality than those generally available on sapphire. Silicon carbide also has a very high thermal conductivity so that the total output power of Group III nitride devices on silicon carbide is, typically, not as limited by thermal dissipation of the substrate as in the case of the same devices formed on sapphire. Also, the availability of semi-insulating silicon carbide substrates may provide for device isolation and  
15 reduced parasitic capacitance. Appropriate SiC substrates are manufactured by, for example, Cree, Inc., of Durham, N.C., the assignee of the present invention, and methods for producing are described, for example, in U. S. Patent Nos. Re. 34,861; 4,946,547; 5,200,022; and 6,218,680, the contents of which are incorporated herein by reference in their entirety. Similarly, techniques for epitaxial growth of Group III  
20 nitrides have been described in, for example, U. S. Patent Nos. 5,210,051; 5,393,993; 5,523,589; and 5,292,501, the contents of which are also incorporated herein by reference in their entirety.

Although silicon carbide may be used as a substrate material, embodiments of the present invention may utilize any suitable substrate, such as sapphire, aluminum  
25 nitride, aluminum gallium nitride, gallium nitride, silicon, GaAs, LGO, ZnO, LAO, InP and the like. In some embodiments, an appropriate buffer layer also may be formed.

Returning to **Figure 1A**, a channel layer **20** is provided on the substrate **10**. The channel layer **20** may be deposited on the substrate **10** using buffer layers,  
30 transition layers, and/or nucleation layers as described above. The channel layer **20** may be under compressive strain. Furthermore, the channel layer and/or buffer nucleation and/or transition layers may be deposited by MOCVD or by other techniques known to those of skill in the art, such as MBE or HVPE.

In some embodiments of the present invention, the channel layer 20 is a Group III-nitride, such as  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  where  $0 \leq x < 1$ , provided that the energy of the conduction band edge of the channel layer 20 is less than the energy of the conduction band edge of the barrier layer 22 at the interface between the channel and barrier layers. In certain embodiments of the present invention,  $x = 0$ , indicating that the channel layer 20 is GaN. The channel layer 20 may also be other Group III-nitrides such as InGaN, AlInGaN or the like. The channel layer 20 may be undoped ("unintentionally doped") and may be grown to a thickness of greater than about 20 Å. The channel layer 20 may also be a multi-layer structure, such as a superlattice or combinations of GaN, AlGaN or the like.

A barrier layer 22 is provided on the channel layer 20. The channel layer 20 may have a bandgap that is less than the bandgap of the barrier layer 22 and the channel layer 20 may also have a larger electron affinity than the barrier layer 22. The barrier layer 22 may be deposited on the channel layer 20. In certain embodiments of the present invention, the barrier layer 22 is AlN, AlInN, AlGaN or AlInGaN with a thickness of between about 0.1 nm and about 10 nm. Examples of layers according to certain embodiments of the present invention are described in United States Patent Publication No. 2002/0167023A1, to Smorchkova *et al.*, entitled "GROUP-III NITRIDE BASED HIGH ELECTRON MOBILITY TRANSISTOR (HEMT) WITH BARRIER/SPACER LAYER" the disclosure of which is incorporated herein by reference as if set forth fully herein. In particular embodiments of the present invention, the barrier layer 22 is thick enough and has a high enough Al composition and doping to induce a significant carrier concentration at the interface between the channel layer 20 and the barrier layer 22 through polarization effects when the barrier layer 22 is buried under ohmic contact metal. Also, the barrier layer 22 should be thick enough to reduce or minimize scattering of electrons in the channel due to ionized impurities deposited at the interface between the barrier layer 22 and a second cap layer 24 (Fig. 1B).

The barrier layer 22 may be a Group III-nitride and has a bandgap larger than that of the channel layer 20 and a smaller electron affinity than the channel layer 20. Accordingly, in certain embodiments of the present invention, the barrier layer 22 is AlGaN, AlInGaN and/or AlN or combinations of layers thereof. The barrier layer 22 may, for example, be from about 0.1 nm to about 10 nm thick, but is not so thick as to

cause cracking or substantial defect formation therein. In certain embodiments of the present invention, the barrier layer **22** is undoped or doped with an n-type dopant to a concentration less than about  $10^{19} \text{ cm}^{-3}$ . In some embodiments of the present invention, the barrier layer **22** is  $\text{Al}_x\text{Ga}_{1-x}\text{N}$  where  $0 < x < 1$ . In particular  
5       embodiments, the aluminum concentration is about 25%. However, in other embodiments of the present invention, the barrier layer **22** comprises AlGaN with an aluminum concentration of between about 5% and about 100%. In specific embodiments of the present invention, the aluminum concentration is greater than about 10%.

10       **Figure 1B** illustrates formation of a protective layer **24** on the barrier layer **22**. The protective layer **24** may be silicon nitride ( $\text{Si}_x\text{N}_y$ ), aluminum nitride (AlN) and/or other suitable protective material, such as silicon dioxide ( $\text{SiO}_2$ ) and/or an oxynitride. Other materials may also be utilized for the protective layer **24** as long as the material may be removed without damaging the underlying barrier layer **22**. For example, the  
15       protective layer **24** could also include magnesium oxide, scandium oxide, aluminum oxide and/or aluminum oxynitride. Furthermore, the protective layer **24** may be a single layer or multiple layers of uniform and/or non-uniform composition.

      In particular embodiments of the present invention, the protective layer **24** is SiN. The SiN may be formed by PVD and/or CVD and may be non-stoichiometric in  
20       compressive or tensile strain. For example, the protective layer may have a stress of between about -100 MPa and about 100 MPa. In certain embodiments of the present invention, the SiN protective layer has an index of refraction at a 633 nm wavelength of from about 1.6 to about 2.2. In particular embodiments, the index of refraction of the SiN protective layer is  $1.98 \pm 0.05$ .

25       In certain embodiments, the protective layer **24** may be AlN. The AlN may be formed by PVD and/or CVD and may be non-stoichiometric in compressive or tensile strain. For example, the protective layer may have a stress of between about -100 MPa and about 100 MPa. In certain embodiments of the present invention, the AlN protective layer has an index of refraction at a 633 nm wavelength from about 1.8 to  
30       about 2.1. In particular embodiments, the index of refraction of the AlN protective layer is  $1.85 \pm 0.05$ .

      The protective layer **24** may also be  $\text{SiO}_2$ . The  $\text{SiO}_2$  may be formed by PVD and/or CVD and may be non-stoichiometric in compressive or tensile strain. For example, the protective layer may have a stress of between about -100 MPa and about

100 MPa. In certain embodiments of the present invention, the SiO<sub>2</sub> protective layer has an index of refraction at a 633 nm wavelength of from about 1.36 to about 1.56. In particular embodiments, the index of refraction of the SiO<sub>2</sub> protective layer is 1.46 ± 0.03.

5           The protective layer **24** is blanket formed on the barrier layer **22** and may be formed by deposition. For example, a silicon nitride layer may be formed by high quality sputtering and/or PECVD. Typically, the protective layer **24** may have a thickness of about 30 nm, however, other thickness layers may also be utilized. For example, the protective layer should be sufficiently thick so as to protect the  
10           underlying layer during a subsequent anneal of ohmic contacts. Layers as thin as two or three monolayers may be sufficient for such purposes. However, in general, the protective layer **24** may have a thickness of from about 10 nm to about 500nm. Also, a high quality SiN protective layer may be grown in-situ with the MOCVD growth of the group III nitride layers.

15           As illustrated in **Figure 1C**, windows are opened in the protective layer **24** for formation of ohmic contacts **30**. The windows may be formed utilizing a patterned mask and a low damage etch with respect to the barrier layer **22** to expose the underlying barrier layer **22**. Examples of low damage etch techniques include etching techniques other than reactive ion etching, such as inductively coupled plasma or  
20           electron cyclotron resonance (ECR) or downstream plasma etching with no DC component to the plasma. For SiO<sub>2</sub>, a low damage etch could be a wet etch with buffered hydrofluoric acid. A selective etch of SiN and/or SiO<sub>2</sub> to an etch stop layer, such as ITO, SCO, MgO or the like, followed by a low damage removal of the etch stop layer could also be performed. For SiN, SiO<sub>2</sub> may be used as an etch stop layer.  
25           In such embodiments, the protective layer **24** may include the SiN, AlN and/or SiO<sub>2</sub> layer as well as the etch stop layer. Thus, in certain embodiments of the present invention, the protective layer **24** may include multiple layers.

          As is further illustrated in **Figure 1C**, with a subsequent photolithography step and evaporation, ohmic metal is patterned to provide the ohmic contacts **30**. The  
30           ohmic contacts **30** are patterned so as to be smaller than the window in the protective layer **24** such that the edges of the ohmic contacts **30** are spaced apart from the protective layer **24**. For example, the edges of the ohmic contacts **30** may be spaced apart from the protective layer **24** by a distance of from about 0.1 to about 0.2 μm. The ohmic contacts **30** should be spaced apart from the protective layer **24** a distance

sufficiently large to allow for misalignment tolerances in the formation and patterning of the ohmic contact metal. If the ohmic contact metal contacts the protective layer 24, the metal may diffuse into the protective layer 24 during subsequent heating steps which may result in a short between a gate contact and the ohmic contact(s) 30.

5 However, the gap between the ohmic contacts 30 and the protective layer 24 should not be so large as to defeat the protective purpose of the protective layer 24 and, thereby, substantially degrade the performance of the device but should not be so small to risk random contact of ohmic material to the protective layer. Thus, for example, in certain embodiments of the present invention, the gap may be from about  
10 0.1  $\mu\text{m}$  to about 0.5  $\mu\text{m}$ .

The ohmic contact material is annealed to provide the ohmic contacts 30. The anneal may be a high temperature anneal. For example, the anneal may be an anneal at a temperature of greater than about 900 °C. Through the use of an ohmic contact anneal, the resistance of the ohmic contacts may be reduced from a high resistance to  
15 less than about 1  $\Omega\text{-mm}$ . Thus, as used herein, the term "ohmic contact" refers to a non-rectifying contact that has a contact resistance of less than about 1  $\Omega\text{-mm}$ . The presence of the protective layer during the high temperature process steps may inhibit damage to the barrier layer 22 that may be caused by such steps. Thus, for example, the sheet resistance of the gate region 21 after the high temperature ohmic contact  
20 anneal may be substantially the same as the sheet resistance of the gate region 21 as-grown (*i.e.* before the contact anneal).

**Figure 1D** illustrates the formation of a gate window. As seen in **Figure 1D**, a mask 26 is formed on the ohmic contacts and the protective layer 24 and patterned to form a window that exposes a portion of the protective layer 24. A recess is then  
25 formed through the protective layer 24 to expose a portion of the barrier layer 22. The recess is formed using the mask 26 and a low damage etch process as described above. In particular embodiments where the ohmic contacts 30 provide source and drain contacts, the recess may be offset between the source and drain contacts such that the recess, and subsequently the gate contact 32, is closer to the source contact  
30 than the drain contact.

As seen in **Figure 1E**, a gate contact 32 is formed in the recess and contacts the exposed portion of the barrier layer 22. The gate contact may be a "T" gate as illustrated in **Figure 1E** and may be fabricated using conventional fabrication techniques. Suitable gate materials may depend on the composition of the barrier

layer, however, in certain embodiments, conventional materials capable of making a Schottky contact to a nitride based semiconductor material may be used, such as Ni, Pt, NiSi<sub>x</sub>, Cu, Pd, Cr, W and/or WSiN. Although it may be undesirable, it is possible that a small gap between the protective layer 24 and the gate contact 32 may arise as a result of, for example, anisotropy of the low-damage etch, resulting in an exposed surface of the barrier layer 22 between the protective layer 24 and the gate contact 32.

**Figure 1F** illustrates the formation of a passivation layer 34. The passivation layer may be blanket deposited on the structure of **Figure 1E**. In particular embodiments, the passivation layer 34 is deposited so as to substantially fill the gap between the protective layer 24 and the ohmic contacts 30 and also the gap between the protective layer 24 and the gate contact 32, if such gap exists. In certain embodiments of the present invention, the passivation layer 34 may be silicon nitride, aluminum nitride, silicon dioxide and/or an oxynitride. Furthermore, the passivation layer 34 may be a single or multiple layers of uniform and/or non-uniform composition.

While embodiments of the present invention have been described with reference to a two mask process for forming opening gate contact windows and forming gate contacts with a gap to the protective layer 24, **Figures 2A and 2B** illustrate operations for forming the ohmic contact windows and the ohmic contacts with a single mask. As seen in **Figure 2A**, a mask 200, such as a photoresist, with a negative bevel may be formed on the protective layer 24. The negative bevel of the mask 200 corresponds to the gap distance between the subsequently formed ohmic contacts 30 and the patterned protective layer 24. The protective layer 24 is isotropically etched using a low damage etch process as described above to provide the contact windows. Thus, the contact windows will be defined by the bottom dimension of the mask 200. A mask layer without a negative bevel could also be used if the etch is isotropic and the low-damage etch is substantially over etched to provide a lateral undercut to the desired spacing.

As seen in **Figure 2B**, ohmic contact metal 300 is evaporated on the resulting structure. The overhang of the mask 200 defines the location where metal is deposited on the exposed barrier layer 22. Thus, the contact metal 300 is spaced apart from the patterned protective layer 24. The mask 200 and the metal 300 on the mask 200 are removed to provide the structure of **Figure 1C**.

Techniques for providing a beveled mask as illustrated in **Figure 2A** are known to those of skill in the art. Furthermore, while the mask **200** is shown as having a bevel, in other embodiments of the present invention, the mask may have a step or other such configuration that provides a mask with two different apparent window sizes for the etch of the protective layer **24** and the deposition of contact material. Thus, for example, multi-layer photoresists are available that have different exposure sensitivity such that a single exposure may provide a mask with an overhang or step such that the window provided by the layer of photoresist proximate the protective layer **24** is large than a window provided by the layer of photoresist spaced apart from the protective layer **24**.

**Figure 3** illustrates fabrication of transistors according to further embodiments of the present invention. As seen in **Figure 3**, the formation of the protective layer **24** prior to ohmic metal deposition may be omitted and the ohmic metal may be deposited and patterned on the barrier layer **22** to provide ohmic contact material regions **30** on the barrier layer **22**. A protective layer **40** is then formed on the gate region of the barrier layer **22** and the ohmic contact material. In particular embodiments of the present invention, the protective layer **40** may be aluminum nitride that is blanket deposited by sputtering. The protective layer **40** may also be materials such as described above with reference to the protective layer **24**.

The anneal of the ohmic contact material regions **30** is carried out with the protective layer **40** in place. The protective layer **40** may then be removed, for example, using a low damage etching technique such as those described above. The gate contact **32** may then be formed, before or after formation of a passivation layer **34**. For example, a layer of silicon nitride could be deposited by sputtering. A gate recess could then be etched, for example, using a low damage etch process as described above, into the passivation layer and the gate formed in the recess. Such a process may provide for the silicon nitride passivation layer maintaining its full thickness to the edge of the "T" gate. Thus, a transistor having a structure such as that illustrated in **Figure 4** may be provided.

Alternatively, the structure illustrated in **Figure 4** may be provided utilizing the fabrication steps illustrated in **Figures 1A-1F**, however, the protective layer **24** may be removed either prior to or subsequent to the formation of the gate contact **32**. In such a case, the protective layer **24** should be removed using low damage etching techniques such as those described above.



**Figure 5** illustrates further embodiments of the present invention where the protective layer **24** is formed to at least about as thick as the ohmic contacts **30**. As seen in **Figure 5**, in such embodiments, the wings of the gate contact **34** may be formed directly on the protective layer **24**. For example, the protective layer **24** may be formed to a thickness of from about 500 to about 5000 Å. A low damage etch through the protective layer **24** would be carried out and the "T" gate **32** formed directly on and through the protective layer **24**. Subsequent overlayer passivation **34** may also be provided, for example, to improve environmental protection of the device.

While embodiments of the present invention have been described herein with reference to particular HEMT structures, the present invention should not be construed as limited to such structures. For example, additional layers may be included in the HEMT device while still benefiting from the teachings of the present invention. Such additional layers may include GaN cap layers, as for example, described in Yu et al., "Schottky barrier engineering in III-V nitrides via the piezoelectric effect," *Applied Physics Letters*, Vol. 73, No. 13, 1998, or in U.S. Patent Publication No. 2002/0066908A1 filed July 12, 2001 and published June 6, 2002, for "ALUMINUM GALLIUM NITRIDE/GALLIUM NITRIDE HIGH ELECTRON MOBILITY TRANSISTORS HAVING A GATE CONTACT ON A GALLIUM NITRIDE BASED CAP SEGMENT AND METHODS OF FABRICATING SAME," the disclosures of which are incorporated herein by reference as if set forth fully herein. In some embodiments, insulating layers such as SiN<sub>x</sub>, or relatively high quality AlN may be deposited for making a MISHEMT and/or passivating the surface. The additional layers may also include a compositionally graded transition layer or layers.

Furthermore, the barrier layer **22** may also be provided with multiple layers as described in United States Patent Publication No. 2002/0167023A1, to Smorchkova *et al.*, entitled "GROUP-III NITRIDE BASED HIGH ELECTRON MOBILITY TRANSISTOR (HEMT) WITH BARRIER/SPACER LAYER" the disclosure of which is incorporated herein by reference as if set forth fully herein. Thus, embodiments of the present invention should not be construed as limiting the barrier layer to a single layer but may include, for example, barrier layers having combinations of GaN, AlGa<sub>N</sub> and/or AlN layers. For example, a GaN, AlN structure may be utilized to reduce or prevent alloy scattering. Thus, embodiments of the

present invention may include nitride based barrier layers, such nitride based barrier layers may include AlGa<sub>N</sub> based barrier layers, AlN based barrier layers and combinations thereof.

5 In the drawings and specification, there have been disclosed typical embodiments of the invention, and, although specific terms have been employed, they have been used in a generic and descriptive sense only and not for purposes of limitation.